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Way to crosscheck μ-e conversion in the case of no signals of $\mu \to e\gamma$ and $\mu \to 3e$

Masato Yamanaka*
Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya 464-8602, Japan
E-mail: yamanaka@eken.phys.nagoya-u.ac.jp

We consider the case that μ-e conversion signal is discovered but other charged lepton flavor violating (cLFV) processes will never be found. In such a case, we need other approaches to confirm the μ-e conversion and its underlying physics without conventional cLFV searches. We study R-parity violating (RPV) SUSY models as a benchmark. We briefly review that our interesting case is realized in RPV SUSY models with reasonable settings according to current theoretical/experimental status. We focus on the exotic collider signatures at the LHC ($pp \to \mu^- e^+$ and $pp \to jj$) as the other approaches. We show the correlations between the branching ratio of μ-e conversion process and cross sections of these processes. It is first time that the correlations are graphically shown. We exhibit the RPV parameter dependence of the branching ratio and the cross sections, and discuss the feasibility to determine the parameters. This paper is based on Ref. [1].

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*Speaker.

1. Introduction

Lepton flavor violation (LFV) is the clearest signal for physics beyond the Standard Model (SM) [2], and searches for LFV have been made [3, 4, 5, 6]. LFV had been found in neutrino oscillation and it indeed requires us to extend the SM so that physics beyond the SM includes LFV. This gives us a strong motivation to search for charged lepton flavor violation (cLFV). New experiments, COMET [7, 8] and DeeMe [9], will launch soon and search μ-e conversion. If COMET/DeeMe observe the μ-e conversion, then with what kind of new physics should we interpret it? Now it is worth considering since we are in-between two kinds of cLFV experiments with muon.

For these several decades, supersymmetric (SUSY) theories have been most studied. These include a source of LFV. In the theories, with the R-parity conservation, $\mu \to e\gamma$ has the largest branching ratio among the muon cLFV [10, 11, 12]. This occurs via the dipole operator and the other two, $\mu - e$ conversion and $\mu \to 3e$, are realized by attaching a quark and an electron line at the end of the photon line respectively, giving an $\mathscr{O}(\alpha)$ suppression. Those branching ratios must be smaller than that of $\mu \to e\gamma$. At this moment, the bounds for the branching ratios are almost same each other. It means if COMET/DeeMe observe the $\mu - e$ conversion, we have to discard this scenario.

It is, however, possible to find a theory in which COMET/DeeMe find cLFV first. The $\mu \to e\gamma$ occurs only at loop level due to the gauge invariance, while other two can occur as a tree process. Therefore in this case we have to consider a theory in which the $\mu - e$ conversion occurs as tree process. So we have to assume a particle which violate muon and electron number. Since $\mu - e$ conversion occurs in a nucleus, it also couples with quarks with flavor conservation. Furthermore it is better to assume that it does not couple with two electrons as we have not observed $\mu \to 3e$.

We consider the case that COMET/DeeMe indeed observe the cLFV, while all the other experiments will not observe anything new. In this case other new physics signals are expected to be quite few, since the magnitude of the cLFV interaction is so small due to its tiny branching ratio. Therefore it is very important to simulate now how to confirm the COMET signal and the new physics. As a benchmark case we study SUSY models without R parity.

2. RPV Interaction and Our Scenario

The gauge invariant superpotential contains the R-parity violating terms [13, 14, 15], $\mathscr{W}_{\rm RPV} = \lambda_{ijk}L_iL_jE^c_k + \lambda'_{ijk}L_iQ_jD^c_k + \lambda''_{ijk}U^c_iD^c_jD^c_k$. Here E^c_i, U^c_i and D^c_i are $SU(2)_L$ singlet, and L_i and Q_i are $SU(2)_L$ doublet superfields. Indices i, j, and k represent the generations. We take $\lambda_{ijk} = -\lambda_{jik}$ and $\lambda''_{ijk} = -\lambda''_{ikj}$. First two terms include lepton number violation, and the last term includes baryon number violation. Since combinations of them accelerate proton decay, we omit the last term.

Our interesting situation is that only μ-e conversion is discovered, and other cLFV processes will not be observed. The situation is realized under the following 3 settings on the RPV interaction:

1. only the third generation slepton contributes to the RPV interactions
2. for quarks, flavor diagonal components are much larger than that of off-diagonal components, i.e., CKM-like matrix, $\lambda'_{ijj} \gg \lambda'_{ijk} (j \neq k)$
3. generation between left-handed and right-handed leptons are different, $\lambda_{ijk} (i \neq k$ and $j \neq k)$.

The setting-1 is realized by the RG evolved SUSY spectrum with universal soft masses at the GUT scale. For the simplicity, we decouple SUSY particles except for the third generation sleptons. The setting-2 is also realized in most cases unless we introduce extra sources of flavor violations. The

setting-3 is artificially introduced to realize the interesting situation. As a result, the Lagrangian is

$$\begin{aligned}\mathscr{L}_{\mathrm{RPV}} = 2\big[&\lambda_{312}\tilde{\nu}_{\tau L}\overline{\mu}P_L e + \lambda_{321}\tilde{\nu}_{\tau L}\overline{e}P_L\mu + \lambda_{132}\tilde{\tau}_L\overline{\mu}P_L\nu_e + \lambda_{231}\tilde{\tau}_L\overline{e}P_L\nu_\mu \\ &+ \lambda_{123}\tilde{\tau}_R^*\overline{(\nu_{eL})^c}P_L\mu + \lambda_{213}\tilde{\tau}_R^*\overline{(\nu_{\mu L})^c}P_L e\big] + \text{h.c.}, \\ &+ \big[\lambda'_{311}\big(\tilde{\nu}_{\tau L}\overline{d}P_L d - \tilde{\tau}_L\overline{d}P_L u\big) + \lambda'_{322}\big(\tilde{\nu}_{\tau L}\overline{s}P_L s - \tilde{\tau}_L\overline{s}P_L c\big)\big] + \text{h.c.}.\end{aligned} \tag{2.1}$$

Processes described by the Lagrangian (2.1) strongly depend on the values of λ'_{311} and λ'_{322}. To clarify the dependence and to discuss the discrimination of each other, we study three cases [1]: [case-I] $\lambda'_{311} \neq 0$ and $\lambda'_{322} = 0$, [case-II] $\lambda'_{311} = 0$ and $\lambda'_{322} \neq 0$, and [case-III] $\lambda'_{311} \neq 0$ and $\lambda'_{322} \neq 0$.

In the scenario we have five types of exotic processes: (1) μ-e conversion in a nucleus, (2) $\mu^- e^+$ production at LHC, (3) dijet production at LHC, (4) non-standard interaction of neutrinos, (5) muonium conversion. In the situation that the μ-e conversion is discovered while other cLFV will never be found, we discuss whether we can confirm the μ-e conversion signal with the five types processes or not. Details of each process and the formulation of reaction rates are given in Ref. [1].

3. Numerical Result

The μ-e conversion is a clear signal for the RPV scenarios, but it is not the sufficient evidence. We must check the correlations among the reaction rates of μ-e conversion, the cross sections of $pp \to \mu^- e^+$ and $pp \to jj$, and so on to discriminate the case-I, -II, and -III, and to confirm the scenario. Fig. 1 shows $\sigma(pp \to \mu\overline{e})$ as a function of $\mathrm{BR}(\mu + N \to e + N)$ in the case-I. Vertical lines show the reach of DeeMe 1-year (4-years) running, COMET phase-I (phase-II), and PRISM. Shaded regions are the excluded region by the SINDRUM-II [5]. Each line corresponds to the dijet production cross section, $\sigma(pp \to jj)$, at $\sqrt{s} = 14$TeV (left panels) and at $\sqrt{s} = 100$TeV (right panels), respectively. For simplicity, we take universal RPV coupling, $\lambda \equiv \lambda_{312} = \lambda_{321} = -\lambda_{132} = -\lambda_{231}$. Fig. 1 shows the clear correlations among $\sigma(pp \to \mu^- e^+)$, $\sigma(pp \to jj)$, and $\mathrm{BR}(\mu^- N \to e^- N)$. Checking the correlations makes possible to distinguish the RPV scenario and other models.

4. Summary and Discussion

We have studied a supersymmetric standard model without R parity as a benchmark case that COMET/DeeMe observe $\mu - e$ conversion prior to all the other experiments observing new physics. In this case with the assumption that only the third generation sleptons contribute to such a process, we need to assume that $\{\lambda'_{311}$ and/or $\lambda'_{322}\} \times \{\lambda_{312}$ and/or $\lambda_{321}\}$ must be large. With the assumptions, we considered the sensitivity of the future μ-e conversion experiments on the couplings and slepton masses. Then with the sensitivity kept into mind we estimated the reach to the couplings by calculating the cross section of $pp \to \mu^- e^+$ and $pp \to jj$. To have a signal of $\mu^- e^+$ both the coupling λ' and λ must be large and hence there are lower bounds for them while to observe dijet event via the slepton only the coupling λ' must be large and hence there is a lower bound on it. In all cases we have a chance to get confirmation of $\mu - e$ conversion in LHC.

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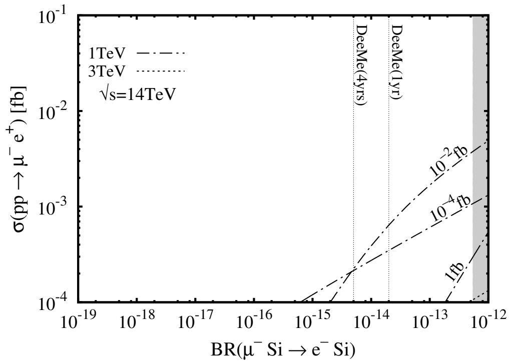
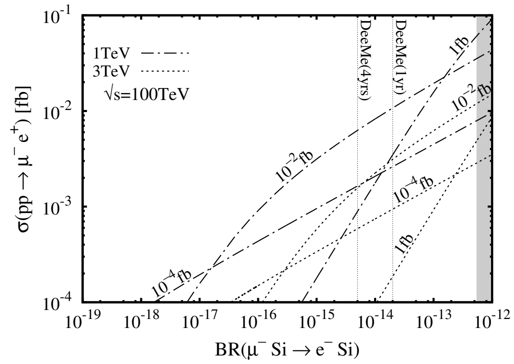
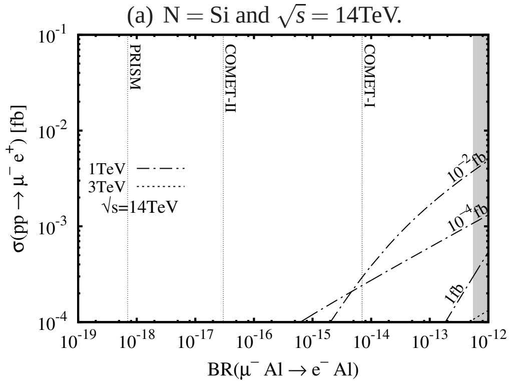


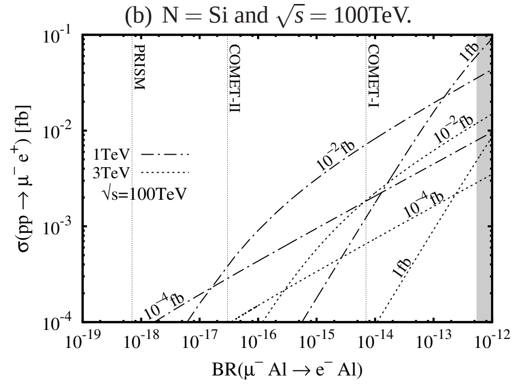
(a) N = Si and $\sqrt{s} = 14$TeV.



(b) N = Si and $\sqrt{s} = 100$TeV.



(c) N = Al and $\sqrt{s} = 14$TeV.



(d) N = Al and $\sqrt{s} = 100$TeV.

Figure 1: $\sigma(pp \to \mu^- e^+)$ as a function of BR$(\mu^- N \to e^- N)$ for each $\sigma(pp \to jj)$ in the case-I. $\sigma(pp \to jj)$ are attached on each line. Results for $m_{\tilde{\nu}_\tau} = 1$TeV ($m_{\tilde{\nu}_\tau} = 3$TeV) are given by dot-dashed (dotted) line. Shaded region is the excluded region by the SINDRUM-II experiment. Left and right panels show the results for $\sqrt{s} = 14$TeV and for $\sqrt{s} = 100$TeV, respectively. We take Si [(a), (b)], and Al [(c), (d)] for the target nucleus of μ-e conversion.

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